CMB-S4

The Next-Generation CMB Experiment

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Origins & Aspirations

CMB-S4 was conceived during the 2013 Snowmass Process as the ultimate ground-based CMB experiment, designed from the outset to

- Cross critical science thresholds across the full range of CMB science.
- Combine the resources and expertise of the entire CMB community.
- Make the full range of CMB science available to the entire CMB community.
- Use existing proven technologies at unprecedented scope and scale.
- Add the unique capacities and capabilities of the DOE laboratories to the long-standing university-based NSF program spanning the Divisions of Physics & Astronomy + Office of Polar Programs.

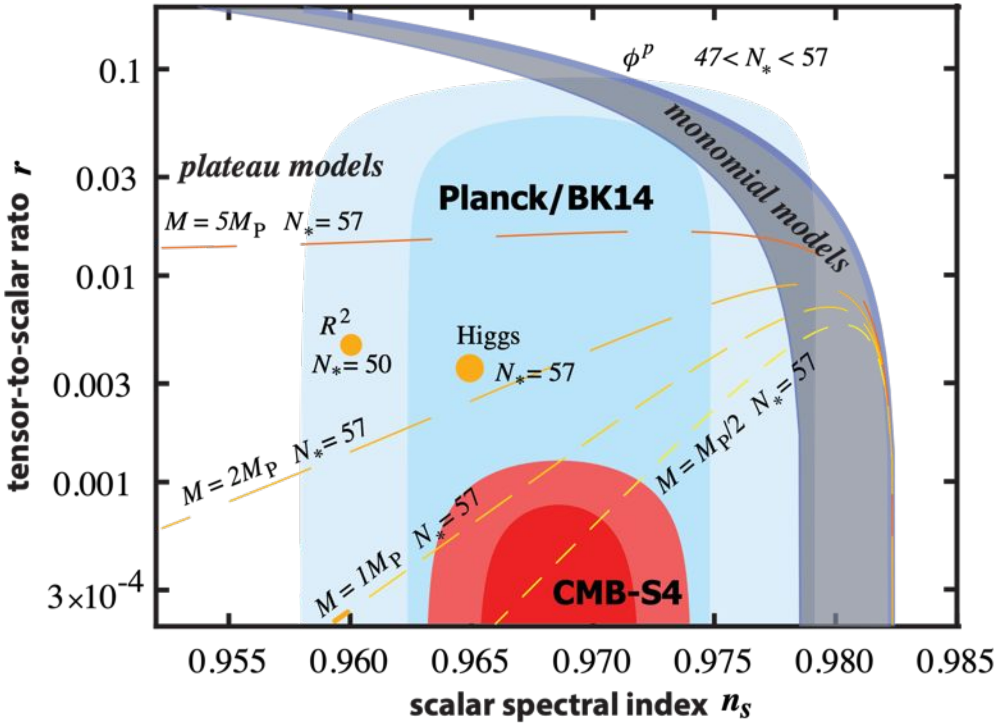
Science Goals

We have converged on four primary science goals spanning CMB/mm-wave science, knowing that much more will be enabled by meeting these.

1. Test models of inflation by measuring (or putting upper limits on) the ratio of tensor to scalar fluctuations.
2. Determine the role of light relic particles in fundamental physics, and in the structure and evolution of the Universe.
3. Measure the emergence of galaxy clusters as we know them today.
4. Explore the mm-wave transient sky.

Primordial Gravitational Waves

Historic opportunity to open up a window to the primordial Universe



All inflation models that naturally explain the observed deviation from scale invariance and that also have a characteristic scale equal to or larger than the gravitational mass scale predict $r > 10^{-3}$.

A well-motivated sub-class within this set of models is detectable by CMB-S4 at 5σ.

CMB-S4 sensitivity to ensures that a non-detection of r would rule out the leading inflationary models, and motivate alternate models for the origin of the universe.

<u>CMB-S4 Science Reqt 1.0</u>:

If r > 0.003: measure at 5*σ*

If r = 0: set r ≤ 0.001 at 2*σ*

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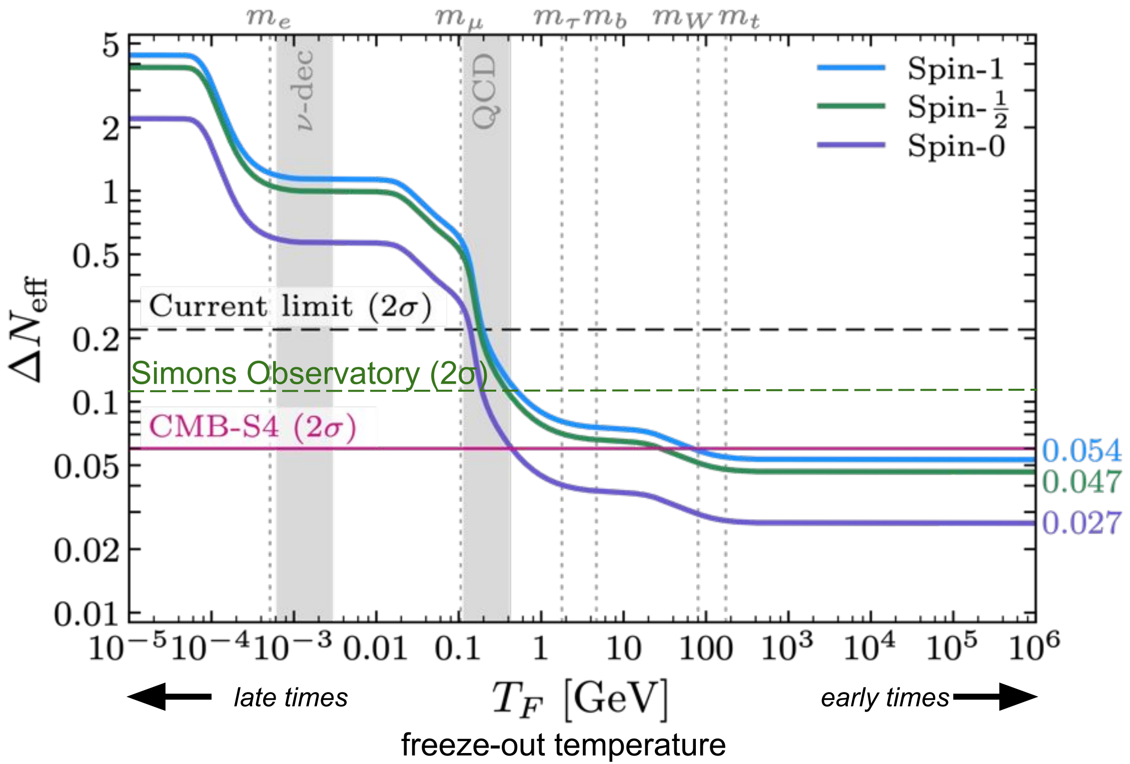
Light Thermal Relics



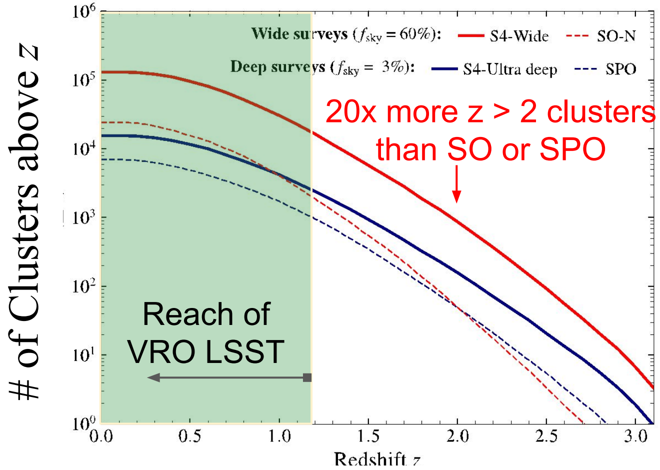
Additional light particles that appear frequently in extensions to the standard model of particle physics will be constrained by CMB-S4.

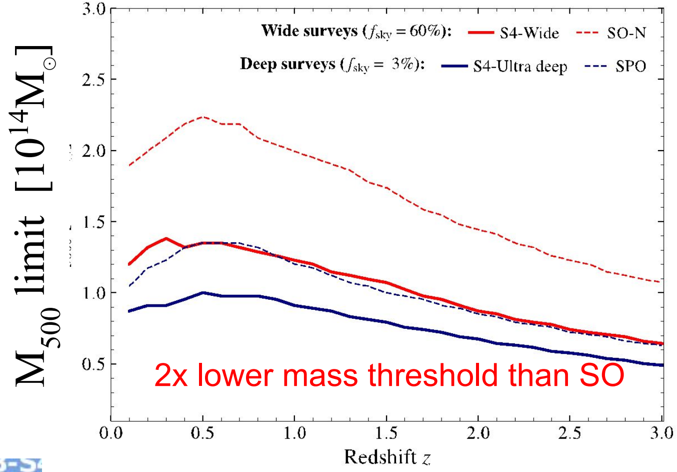
CMB-S4 requirement to detect all light relics that decoupled after the start of the QCD transition, providing orders of magnitude improvement on the freeze-out temperature of any thermal relic.

<u>CMB-S4 Science Reqt 2.0</u>:

ΔNeff < 0.06 at 2σ

High Redshift Galaxies and Galaxy Clusters





Legacy Catalog of massive galaxy clusters out **to the highest redshifts at which they exist**

- Including hundreds of clusters at z ≳ 2, at the peak of cosmic star formation, which will not be sampled through other surveys, such as VRO.

Legacy Catalog of high-redshift galaxies out to the highest redshifts at which they exist.

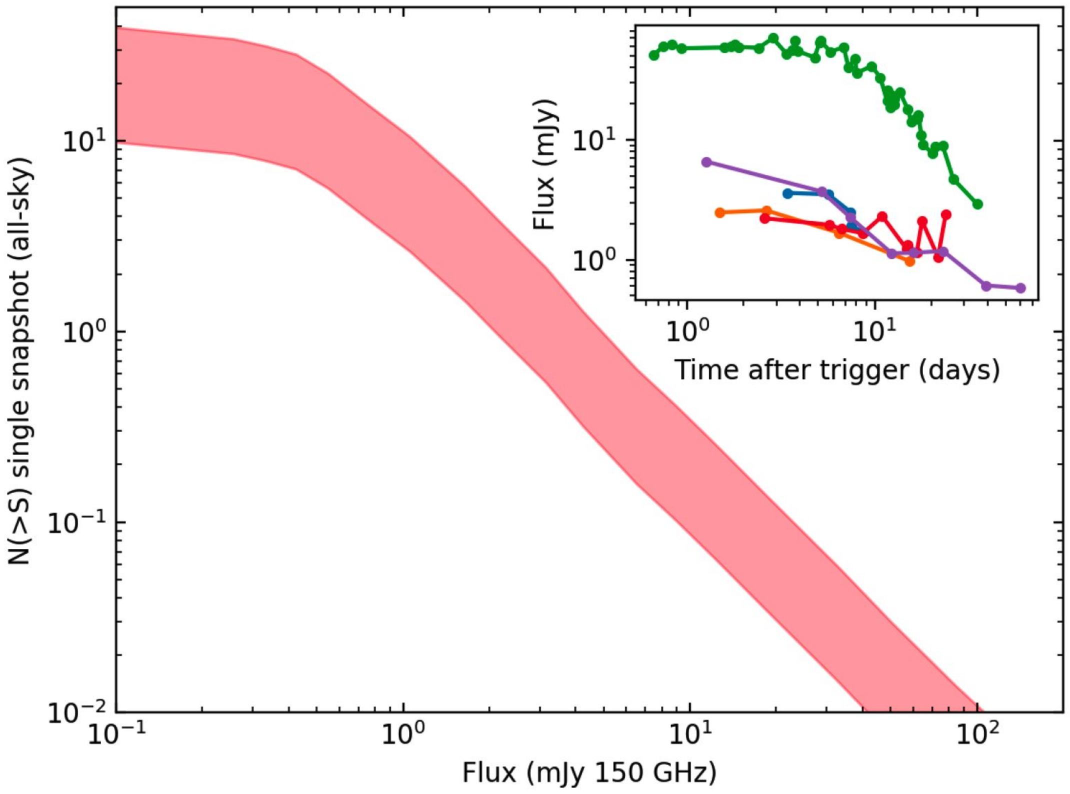
- Including **protoclusters** at z > 4

CMB-S4 Science Reqt 3.0:

Detect at 5σ all galaxy clusters at z > 1.5 with integrated Compton $Y_{SZ,500}$

- **above 10^{-12} over 50% of the sky**
- **above 10^{-13} over 3% of the sky**

Millimeter-Wave Transients



At the sensitivity and resolution required by its other science goals, CMB-S4 is also a unique mm-wave observatory.

By incorporating high-cadence observations over a common field we can detect mm-wave transients and add extend the spectrum of Multi-Messenger Astronomy into the microwave.

CMB-S4 Science Reqt 4.0:

> **Detect gamma-ray burst afterglows brighter than 30 mJy at 95 and 150 GHz**

Measurement Requirements

SCIENCE		FREQUENCY COVERAGE	ANGULAR RESOLUTION	MAP DEPTH	SKY AREA	CADENCE
r	Primordial BB Lensing BB	Wide	Low Moderate	Ultra-Deep Ultra-Deep	Small	-
N_{eff}		Moderate	High	Deep	Large	-
Clusters		Wide	High	Deep Ultra-Deep	Large Small	-
GRBs		Narrow	High	Deep	Large	Daily

Full science suite requires 3 surveys:

1. Ultra-deep, small area, low resolution (r - primordial)
2. Ultra-deep, small area, high resolution (r - lensing, clusters)
3. Deep, wide area, high resolution (N_{eff}, clusters, GRBs)

Detailed Measurement Requirements

We have derived detailed measurement specifications for each of our three surveys that collectively meet the full set of our design-driving requirements:

Ultra-Deep Low Resolution "r" Survey: 3% Sky	Frequency	GHz		30	40	85	95	145	155	220	270
	QU noise	uK-arcmin		3.50	4.50	0.88	0.78	1.20	1.30	3.50	6.00
	Angular resolution	arcmin		72.80	72.80	25.50	22.70	25.50	22.70	13.00	13.00
	Ell-knee	≤		60	60	60	60	65	65	65	65
Ultra-Deep High Resolution "Delensing" Survey: 3% Sky	Frequency	GHz	20	27	39		93	145		225	278
	QU noise	uK-arcmin	15.00	21.00	4.60		0.71	0.65		2.10	4.90
	Angular resolution	arcmin	13.40	8.60	5.90		2.60	1.60		1.20	1.00
	Ell-knee	≤	"Level seen by SPT-3G"								
Deep-Wide High Resolution "Legacy" Survey: 66% Sky Daily Cadence	Frequency	GHz		27	39		93	145		225	278
	I noise	uK-arcmin		22.28	12.18		1.97	2.18		7.20	17.62
	QU noise	uK-arcmin		31.51	17.23		2.79	3.09		10.18	24.92
	Angular resolution	arcmin		7.40	5.10		2.20	1.40		1.00	0.90
	Ell-knee	≤	"Level seen by AdvACT"								

Experiment Design

The experiment design spans the instruments and their observations

Together they must meet the measurement requirements

Instrument design

- Resolution (telescope apertures & quality of mirrors)
- Frequency coverage (detector bandpasses)
- Depth (numbers of detectors)

Observation design

- Depth (duration of observation)
- Sky area (survey strategy)
- Cadence (survey strategy)

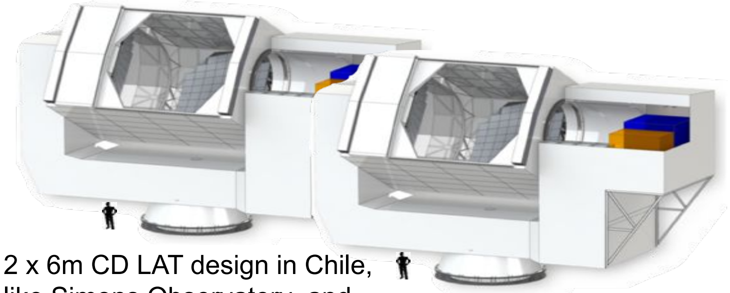
Telescopes

Deep-Wide Survey:

- LAT: 2 x 6m Cross-Dragone telescopes with 18-tube/1-wafer cryostats and no ground shield [cf. CCAT-prime, SO]

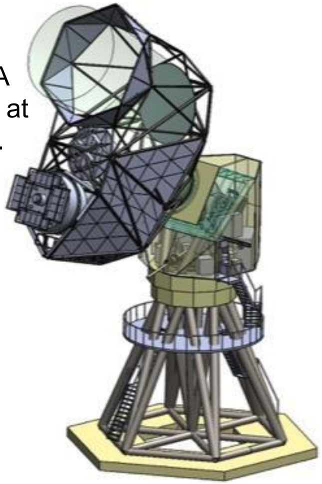
Ultra-Deep Surveys:

- SAT: 18 x 0.55m telescopes with 3-shooter cryostats & ground shields [cf. BICEP Array, SO]
- LAT: 1 x 5m Three-Mirror Anastigmat telescope with an 18-tube/1-wafer cryostat and no ground shield.



2 x 6m CD LAT design in Chile, like Simons Observatory and CCAT-prime.

18 x 0.55m three-shooter SAT design, like BICEP Array.



1 x 5m TMA LAT design at South Pole.

Detectors, Readout, Modules

Detectors:

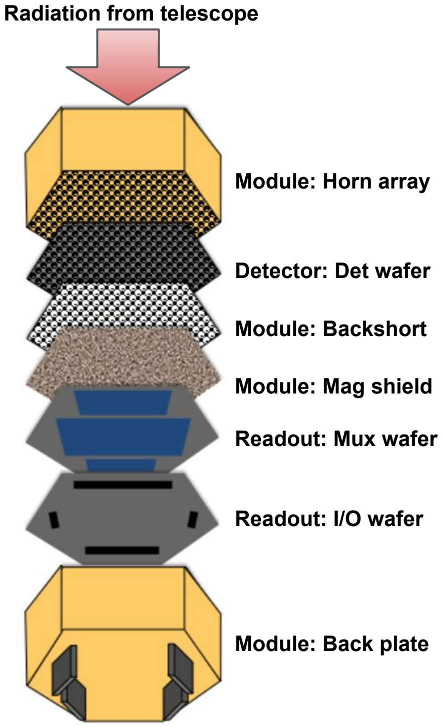
- 550,824 transition-edge sensors on 503 wafers of horn-coupled dichroic pixels over 9 frequency bands [cf. SPT-3G, SO]

Readout:

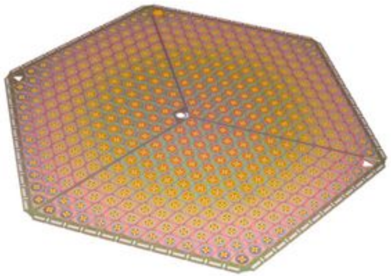
- 8493 modules of 64-way time-domain multiplexed readout [cf. AdvACT]

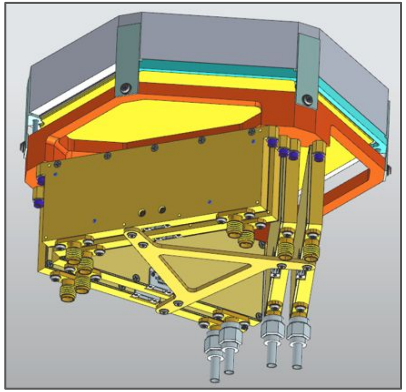
Module Assembly & Testing:

- 503 modules including 100mK cryoelectronics



Detector + readout module





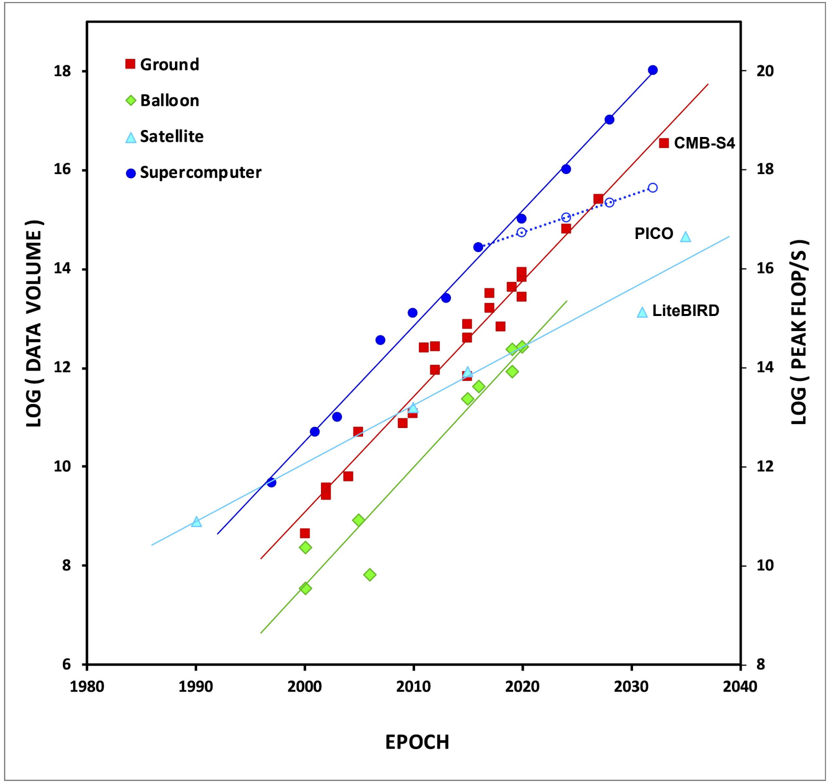
Data Acquisition & Management

Data Acquisition

- Handle 6 Gbit/s of data coming off the telescopes for 7 years.
- Manage the coordinated operation of 21 telescopes.

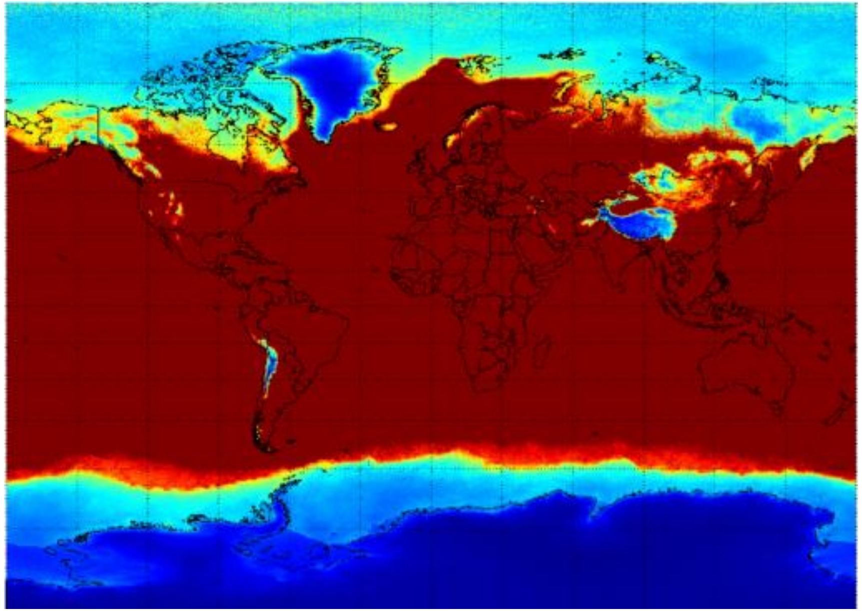
Data Management

- Reduce 60PB of data to maps - 10x the volume of all previous CMB experiments combined - using an integrated Superfacility of DOE HPC & NSF HTC computing resources.
- Simulate and reduce the full data volume 1000s of times.



Survey Sites

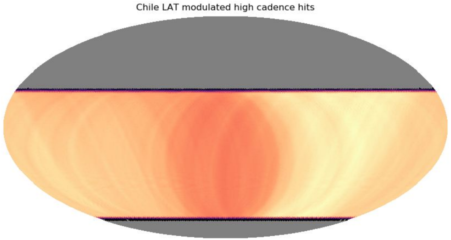
- Ground-based CMB observations are limited by the atmosphere: we need high, dry, sites.
- The South Pole and Chilean Atacama are the highest, driest sites.
- The US CMB community has a long history of working at both, and significant infrastructure is already in place for CMB-S4 precursors (South Pole Observatory; Simons Observatory & CCAT-prime)



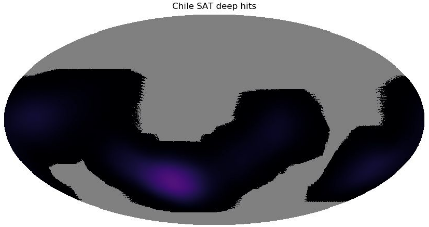
Mean precipitable water vapor across the globe. Candidate sites (dark blue) are the South Pole, Chilean and Argentinian Atacama Desert, Tibetan Plateau & Greenland.

Survey Design

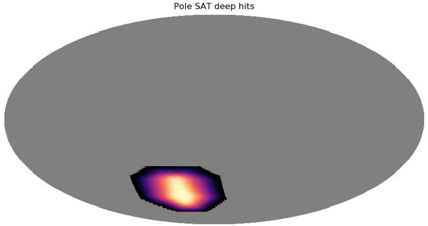
- CMB-S4 is unique in having *two* exceptional observing sites available.
- The biggest difference between the sites is in the types of sky surveys their latitudes can support.
  - Wide-area surveys can only be performed from Chile; only fraction of the survey area can be observed with a daily cadence.
  - Compact ultra-deep surveys can only be performed from the South Pole; the full survey area can be observed with a daily cadence.
- Our survey requirements can best be met by using both sites.



Chile wide survey hitmap



Chile deep survey hitmap



South Pole ultra-deep survey hitmap

CMB-S4

Timeline & Status

- 2013 - Conceived in Snowmass Process
- 2014 - Recommended by the Particle Physics Project Prioritization Panel under all budget scenarios [DOE, NSF Physics]
- 2015 - Identified by the National Academy of Sciences/National Research Council as one of three strategic priorities for Antarctic science [NSF OPP]
- 2017 - Concept Definition Taskforce report unanimously approved by Astronomy & Astrophysics Advisory Committee
- 2019 - DOE takes Critical Decision 0, identifying mission need
- 2020 - Astro2020 performs full Technical Risk And Cost Evaluation
- 2021 - Astro2020 report pending … [NSF Astronomy]

Future Plans & Summary

Assuming recommendation by Astro2020:

- DOE + NSF joint construction project
- Phased commissioning starting in the late 2020s
- 7 years of operations through the mid 2030s

With 21 telescopes at the South Pole and in the Chilean Atacama desert surveying the sky with 550,000 cryogenically-cooled superconducting detectors for 7 years, CMB-S4 will deliver transformative discoveries in fundamental physics, cosmology, astrophysics, and astronomy.